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Seeing the wood for the trees: recent advances in the reconstruction of woodland in archaeological landscapes using pollen data

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Abstract

Pollen sequences record the vegetation cover of past landscapes, but translating a pollen diagram into a landscape reconstruction is not straightforward. This paper reviews recent advances in the reconstruction of woodland cover from palynological data and shows how they have been used to address three archaeologically relevant problems:

- The detection of woodland presence and extent in a largely open landscape
- The reconstruction of the habitat context of a specific archaeological site
- The detection of woodland management

Pollen surface samples which can be directly related to contemporary vegetation cover are shown to be useful both in their own right and as the basis for calibration of models of pollen dispersal and deposition. These models can be used as a foundation for quantitative reconstruction of past landscapes, for example using the Multiple Scenario Approach, or as a tool for construction and testing of hypotheses and to inform selection of coring sites.

We argue that surface sample studies and simulation approaches are improving the scientific basis of reconstruction of past landscapes, and that these approaches offer new opportunities for communication and collaboration between archaeologists and environmental specialists.

Keywords: coppicing, cultural landscapes, environmental archaeology, palynology, simulation, woodland

1. Introduction

The division between wooded and non-wooded habitats is a fundamental determinant of the human experience of terrestrial landscapes. Woodlands have distinctive structure, vegetation, and microclimates, and offer a range of resources to human inhabitants. Their presence affects visibility and mobility within the wider landscape, land use, and economic and subsistence strategies. Throughout the temperate woodland biome which is the potential vegetation for much of northern and central Europe, the Holocene vegetation history can be divided into two phases. In the first, Mesolithic people lived within and at the edges of the woodlands, and whilst their activities had detectable effects on some woodland landscapes (Charman 1994; Innes *et al.* 2010; Bishop *et al.* 2015; Ryan and Blackford 2015), the overall extent of woodland remained broadly constant until the second phase, when Neolithic cultural groups began to practice forms of agriculture including the introduction of domesticated herbivores and more permanent forms of settlement. The overall landscape dynamic story of this second phase is the opening up and removal of woodland cover, at different times and rates in different locations. Historical analogues, for example the Medieval of the British lowlands (Rackham 1990), demonstrate that once a landscape becomes predominately open any remaining woodland acquires greater value both economically and symbolically. Parish alignments often show how remaining woodland fragments were positioned at the junction of several parishes to allow all access to the woodland resource, and documentary records show the economic value placed on woodland and woodland products, and the legal effort put into the protection of woodland. As open vegetation habitats became the main land cover, remaining woodland became increasingly curated, domesticated and managed.

A key tool for the reconstruction of past land-cover, and thus the history of these dynamics and of the context of prehistoric and early historic human populations, is pollen analysis. Pollen and spores are produced by vascular plants, ferns and mosses as part of their reproductive cycles, and are designed to disperse widely in the landscape. Some achieve their biological purpose, and some are deposited into preserving environments such as lakes or mires, where accumulating sedimentary archives preserve them in chronological order for thousands of years. Different species and genera have different reproductive strategies, therefore produce different amounts of pollen and pollen of different shapes and sizes, which in turn affects how far the pollen is transported and how much arrives in a preserving context. Climate, hydrology, topography and landscape structure may also affect the forming pollen signal. Interpreting the pollen record in terms of the details of a past landscape is therefore a complicated and not fully understood process.

Reconstruction of landscapes from pollen records is only semi-objective, having a relatively weak empirical base, and can be constrained by the expectations and experiences of the individual analyst. Much of the literature presenting pollen records from specific locations offers a narrative reconstruction of past landscape dynamics, informed to some degree by both ecological and archaeological understandings of environmental processes, and by guidelines derived from various studies of the pollen signal formation process (see e.g. Moore *et al.* 1991), such as using a conceptual model to estimate the spatial area of landscape represented by a pollen record (Jacobson and Bradshaw 1981) or drawing on known associations between the abundance of plants producing particular pollen types and different types of landscape activity (Behre 1981).

Regional scale patterns of woodland composition and timing of woodland loss provide a useful general framework for landscape history, and have been reconstructed from simple metrics like the proportion of tree pollen to non-tree pollen (AP:NAP ratios – arboreal pollen: non-arboreal pollen) (Frenzel *et al.* 1994; Sugita *et al.* 1999). Regional syntheses have also used semi-quantitative and quantitative methods such as isopoll mapping (Bernato and Webb 1977; Huntley and Birks 1983; Birks 1989), Biomisation (Prentice *et al.* 1996, Williams *et al.* 2004), or Modern Analogue Matching (Overpeck *et al.* 1985, Ohlwein and Wahl 2012). A search for better interpretation and quantification of the landscape meaning of a change in the AP:NAP ratio provided the starting point for work over the last 16 years in improving the quantitative reconstruction of past land-cover using process-based modelling approaches (Sugita *et al.* 1999; Gaillard *et al.* 2008; Gaillard *et al.* 2010; Trondman *et al.* 2015). These techniques use algebraic models of the taphonomic process linking pollen assemblages with the vegetation that produces them to obtain quantitative measures of vegetation cover from pollen data. Estimates of the proportion of woodland in a region are a useful starting point, but have limited relevance to the study of specific archaeological landscapes or sites - people live and act at a finer spatial scale, on the order of a few kilometres, whereas these regional reconstructions apply to areas of around 100km in radius.

Two current approaches using the same underlying models of pollen dispersal and deposition (Prentice 1985; Prentice 1988; Sugita 1993; Sugita 1994) are summarised in Figure 1: these are the Multiple Scenario Approach (MSA; Bunting and Middleton 2009) and the Landscape Reconstruction Algorithm (LRA; Sugita 2007a, 2007b). The MSA uses ecological information to develop hypotheses about the past distribution of different plant communities. By combining the range of values for distribution (e.g. placing treeline anywhere between 50 and 300 m) for each community, and randomly placing patches of vegetation into suitable locations in different proportions, thousands of

possible vegetation maps are produced. The pollen assemblage that would have been delivered to the defined target point (i.e., the location of an actual pollen sequence) is then simulated for each hypothetical landscape. These simulated pollen assemblages are statistically compared with the actual palaeoecological assemblages to identify those scenarios which provide the closest match to the observed pollen data, and thus probable past vegetation mosaics. The LRA produces estimates of vegetation abundance within the relevant source area of the target pollen sequence (which can vary from hundreds of metres to a couple of kilometres depending on the characteristics of the site sampled; Sugita 1994), but provides no information on the spatial patterning of the different vegetation communities inside that radius. Rapid advances in personal computing in recent years have made these modelling approaches much more widely available within the palynological research community, but significant challenges relating to model calibration remain.

This paper explores recent applications of a suite of methods to the interpretation of pollen signals in archaeological landscape investigations, using surface sample studies, simulations of the pollen-vegetation relationship and a hypothesis-testing approach to consider three types of problem:

- The detection of woodland presence and extent in a largely open landscape
- Reconstructing the habitat context of a specific archaeological site combining on-site and off-site pollen records
- Detecting woodland management

We argue that surface sample studies and simulation approaches are improving the scientific basis of reconstruction of past landscapes and that these approaches offer new opportunities for communication and collaboration between archaeologists and environmental specialists.

2. Methods for the quantitative interpretation of pollen records

‘Natural’ pollen traps such as lake surface sediments, moss polsters and surface soils are present in sufficient quantity in most landscapes to enable modern pollen assemblages to be compared with the contemporary vegetation, allowing better understanding of the taphonomic processes involved in pollen assemblage creation. Where these are not widely available, artificial pollen traps can be placed within stands of different vegetation types to allow comparison of modern pollen rain and contemporary vegetation. Essential input parameters for the LRA and MSA include estimates of relative pollen productivity (RPP) for the taxa of interest, which can be extracted from measurements of modern pollen assemblages and vegetation cover using extended R-value analysis

(Parsons and Prentice 1981). Modern pollen assemblages are therefore key to reconstructing past vegetation cover from pollen records using these approaches, as well as providing valuable insights in their own right.

Current reconstruction methods, whether quantitative or qualitative, assume that RPP is a constant, both in time and space, and therefore that changes in pollen proportions at different levels in a core sequence reflect changes in the abundance or position of vegetation communities rather than a change in the amount of pollen produced by individual plants, and that it is possible to compare pollen assemblages of the same age from different parts of a landscape and again interpret differences in terms of plant abundance rather than pollen production. It is clear from published estimates of RPP that this is not always the case, and that pollen production can vary across the geographic range of a taxon (Broström *et al.* 2008; Mazier *et al.* 2012). Published estimates are currently limited in geographic scope, with the majority coming from northern Europe and North America. Estimates of RPP have recently become available for sites in southern Africa (Duffin and Bunting 2008), Greenland (Bunting *et al.* 2013), China (Li *et al.* 2011; 2015) and Siberia (Niemeyer *et al.* 2015), and much effort is currently being invested to obtain estimates for other regions so that model-based approaches to vegetation reconstruction can be applied globally.

Another approach to vegetation reconstruction based on pollen data uses the dispersal and deposition model within a multiple hypothesis testing framework, working with a restricted number of simplified landscape arrangements to better understand the responsiveness of the pollen signal to hypothesised differences or changes. This approach lies between the traditional narrative approach and the fully quantified outputs of the LRA or MSA, and is particularly suited to archaeological questions regarding models of land-use, resource availability and interaction of prehistoric communities with the environments that they inhabited. GIS-based models of vegetation mosaics have been used to test hypotheses regarding the expansion of mixed agriculture into upland environments on Exmoor, south-west England, during the early medieval period (Fyfe 2006). This approach has also been used to characterise landnam landscapes and investigate the effects of the elm decline on the nature of the remaining vegetation in the Irish Midlands (Caseldine and Fyfe 2006), and to demonstrate that during the Neolithic, the western seaboard of Ireland would have been much more attractive to agriculturalists than it appears today (Caseldine *et al.* 2007). It is inevitable that there will be a certain degree of equifinality with this approach, with multiple ecologically distinct landscapes producing very similar pollen signals, and it is likely that this will lead to development of hypotheses for further testing (Bunting and Middleton 2009). The approach does,

however, allow certain hypotheses to be rejected if they are shown to have been very unlikely to have produced the pollen assemblages under study (Caseldine *et al.* 2008). The Multiple Scenario Approach (Bunting and Middleton 2009) represents an extreme form of the multiple hypothesis approach, making use of multiple script-generated replicates of scenarios for each set of criteria to incorporate variations in the random placement of landscape elements, and calculating the 'fit' of simulated and actual pollen assemblages across 10^3 - 10^5 scenarios where hypothesis testing usually considers 10^1 - 10^2 alternatives, increasing the possibility of identifying unexpected equifinal solutions.

Differences in the arrangement of trees within a landscape create perceptibly different environments, even if the species composition and cover proportion is the same, and the size of a sediment body affects the ability of the pollen signal it contains to detect variations in local land-cover (Sugita 1994). Figure 2 uses a simulation approach to illustrate this, using four simple land-cover arrangements combining woodland and grassland, all of which consist of 10% trees, 90% grassland. From left to right, the landscapes simulate a wood-pasture or parkland with single trees randomly located, a divided landscape with areas of grassland and wood-pasture, a landscape with small scattered copses of trees among grassland, and a landscape with a single woodland in an open landscape. All four were set into a wider landscape which was 50% wooded (see Appendix for details of simulation parameters). Pollen assemblages were simulated for two mires situated in the bottom left and top right of each of the landscape scenarios, with small mires (20m radius) in Figure 2a and medium sized mires (100 m radius) in Figure 2b.

Visibility and traversability would differ markedly between these landscapes and within these landscapes. The microclimate and associated flora and fauna of woodland, copse, wood-pasture and open grassland are all distinctive, and different landscape resources would be presented by each scenario to wild and domesticated animals and to human populations. Each of these landscape options could arise as a product of specific cultural and economic decisions on the part of a local human population, either through intentional design or as the emergent result of many small decisions and actions.

Comparing the range of proportions of tree pollen in Figure 2 clearly illustrates that the variability of the pollen signals within and between landscape scenarios decreases as the size of the mire increases – for a large site, 500m or more in radius, the variations in organisation of the trees would be palynologically invisible. The arrow-heads indicate assemblages with very similar proportions of

tree pollen (55-58%); they clearly illustrate the problem of equifinality discussed above, where ecologically distinct landscapes produce very similar pollen signals. When the pairs of sites are considered, though, some differences between the landscapes become apparent – greater variation between samples shows greater variation in local tree density. This simple exercise illustrates:

- the challenges of interpreting percentages of tree pollen in terms of percentage tree cover – the sixteen simulated pollen assemblages shown in Figure 2 come from a landscape containing 10% tree cover, yet the tree pollen values range from 44% to 90%,
- the increased information presented by synthesis of multiple cores within one landscape to constrain reconstructions of land-cover, and
- the potential of using simulations to construct a hypothesis test which can drive targeted pollen core collection and analysis; for example, in scenarios 2 and 4, the lower left mire (positioned in the grassland) has a very similar pollen signal regardless of land-cover, whilst the pollen signal from the upper right mire (positioned in either wood-pasture or woodland) clearly differs between land-cover scenarios.

3. Case study 1: detecting woodland fragments in a largely open landscape

Woodland decline following Neolithisation proceeded at different rates and to different endpoints, depending on geographic location (see review for Scotland by Tipping 1994). In Orkney, it has been suggested that woodland was rare by the mid-Neolithic (Farrell *et al.* 2014), whereas extensive tracts of woodland persisted into the historic period and even into the present, for example in Abernethy in eastern Scotland (Birks 1970). Once woodland became comparatively rare, the fragments that did remain are likely to have been of disproportionate importance to the inhabitants of the landscape, and therefore subject to management (Dugmore *et al.* 2007; Schofield and Edwards 2011). A key research question in reconstructing landscape in the later Holocene is often the persistence and survival of woodland as a resource.

Figure 3 shows results from an application of the Multiple Scenario Approach to reconstructing past land-cover for the Coigach peninsula, a 15 km x 20 km block of landscape in north-west Scotland, (Figure 4) (after Bunting *et al.* 2007). Environmental constraints for the possible land-cover were set using a digital elevation model (altitude, slope and aspect) and a palaeogeography map (to incorporate late-Holocene sea-level change). Dominant communities were inferred from pollen data from a wetland basin at Badentarbet (Bunting and Tipping 2004) and other palaeoecological evidence (e.g. radiocarbon dated tree stumps; Bridge *et al.* 1990), and ecological preferences (e.g.

alder is more likely to be found in stream beds and on lake margins, tree line was set around 400 m asl) included, but a large range of variation in the position and proportional coverage of different vegetation types was allowed for. Between 10,000 and 80,000 possible landscape scenarios were simulated for five time slices, corresponding with periods of stability in the Badentarbet pollen record. Pollen counts were simulated for the coring point in each scenario, and compared statistically with the mean pollen counts from the relevant pollen zone to identify those scenarios which could be considered to be possible reconstructions of past land-cover, since they produced pollen assemblages most similar to those deposited from the actual land-cover at the time. Figures 3a and 3b show examples of possible reconstructions of past land-cover for 5200BP and 300BP, and Figure 3c summarises the overall woodland-open land proportions in the chosen reconstructions for each time-slice.

Even within this comparatively small landscape, the variability of woodland survival is apparent. Surviving woodland is less diverse than was the case in prehistory, and trees mostly persist today in a restricted subset of habitats. These areas typically offer better drainage and less grazing pressure due to restricted access for people and grazing animals, with some sheltered microhabitats which can serve as regeneration niches for trees outside of the protection of wider woodland, and are typically on steep rocky slopes, in areas of tumbled rock, or lining stream gullies, which are not favourable for sediment accumulation and thus pollen record formation. Since sedimentary archives and therefore pollen records are not randomly distributed, inevitably this means that the palynological visibility of different parts of the landscape varies.

Surface sample studies and simulations provide some insights into the pollen signal of woodland fragments within the landscape, which can be used to interpret palaeoecological records (Figure 5). Studies of the modern pollen rain in surface samples located around woodland fragments in upland landscapes show a clear 'edge effect' (e.g. Turner 1964; Tinsley and Smith 1978; Gearey and Gilbertson 1997; Bunting 2002), with elevated tree pollen within a few tens of metres of the woodland edge. Figure 5a shows an example (Bunting 2002) plotted along with simulation results from a simple model based on the same landscape (see Appendix for simulation details). The broad pattern of the pollen signal is replicated in the simulation, although the edge effect is less marked, probably due to model omissions (for example, all modelled pollen is released at the same height, whereas a woodland-moorland ecotone typically has an abrupt height change; most of the species typical of upland woodlands tend to flower more freely in the higher light regime of the woodland edge and therefore may have locally higher pollen productivity).

Figure 5b shows total tree pollen curves over time from cores taken from small basins within blanket peat at Hobbister, Orkney (Farrell 2015; Figure 4), which have a marked general resemblance to Figure 5a. Two cores were collected within 80 m of each other, A from the deepest peat and B from the location closest to an archaeological find point. Although the ages of the onset of peat accumulation differ between these locations, each shows a similar pattern of tree pollen proportions, with a decline from an initial high value to a stable 'background' value; the shape of this decline has similarities with the observed surface sample signal seen in Figure 5a. These records are interpreted as showing changes in the position of woodland stands relative to the coring location over time, as the peat encroaches across the landscape. This pollen record illustrates how small pieces of woodland in a largely treeless landscape can be 'invisible' in some pollen records but detected by others (compare cores A and B around 4500-4000 BP), and supports arguments for the persistence of some woodland in apparently 'treeless' landscapes well after the main woodland declines observed in larger site records (e.g. Farrell *et al.* 2014); these small pieces of woodland would have presented an important resource for human inhabitants and could have been subject to active management (Dugmore *et al.* 2007; Schofield and Edwards, 2011).

Assumptions of treelessness in later prehistory, especially those based on pollen records from the centres of medium and large sized basins, probably need to be revisited in many cases. Records from individual sites are often published with caveats, but the nuance of interpretation is easily lost in synthesis or transfer of information. Simulations offer an opportunity to investigate the amount of woodland that could actually be present but not be clearly separated from a long-distance signal in a pollen diagram, therefore allowing some quantification of the range of possibilities, and also to investigate the sensitivity of different sites in a landscape. Identifying coring locations close to those habitats which favour woodland persistence, such as the small hollows used to study woodland dynamics in Glen Affric (Shaw and Tipping 2006), and consideration of pollen records from marginal peatland positions as well as centrally located ones, may also improve our understanding of woodland persistence in largely open landscapes.

4. Case study 2: reconstructing landscape context for a specific site

Reconstructions of past land-cover can also make useful contributions to the understanding of single archaeological sites. This can be illustrated by virtual reality reconstructions of the Neolithic landscape at Temple Wood stone circle in Kilmartin Glen, Scotland (Winterbottom and Long 2006; see Figure 4). The site at Temple Wood was used over an extended period of time from the Neolithic

onwards, and may in fact have been a series of monument types, evolving over time from an open stone circle to an embanked stone circle or possibly a ring cairn (Bradley 1998). This continued remodelling of the site effectively converted an open monument into a closed one. Palynological data from nearby sites indicate the presence of hazel-oak-elm woodland on the valley sides and birch-hazel woodland on the valley floor, which was disturbed and gradually opened up during the Neolithic. Two contrasting landscape hypotheses were therefore created and visualisations produced for the Temple Wood stone circle. Within the closed canopy woodland scenario, the monument is largely concealed and cannot be seen from the surrounding landscape until the viewer is very close to it, perhaps implying that access was restricted to those who already knew where the site was. In the later, more open landscape the monument is visible from much further afield, and it may be that deforestation and opening up of the landscape necessitated the alteration of the monument itself from open to closed, to maintain the restricted property once the vegetation ceased to provide it (Winterbottom and Long 2006). The Temple Wood reconstructions serve to demonstrate how contrasting land-cover hypotheses can affect the setting and interpretation of archaeological sites. However, the technology used to create virtual reality reconstructions is often so advanced that they may be uncritically accepted as being scientifically accurate, with no consideration of the degree of uncertainty associated with the data on which they are based.

A similar approach was taken by Tipping *et al.* (2009) to define spatial patterns of land-use around an early Neolithic timber 'hall' at Warren Field in north-east Scotland (Murray *et al.* 2009; see Figure 4). Previous palaeoecological studies in the region (reviewed by Tipping 1994), including records from Loch of Park (Vasari and Vasari 1968) and the Red Moss of Candyglirach (Clark and Edwards 2004), both large natural basins within 5 km of Warren Field, show that the Neolithic vegetation surrounding Warren Field would have been oak-hazel woodland, and no evidence of early Neolithic woodland disturbance is seen. However, pollen assemblages recovered from a small (c. 1.5 m diameter) pit feature within the Warren Field 'hall' suggest relatively open vegetation influenced by anthropogenic activity, with evidence for the presence of hazel scrub woodland and open-ground taxa including buttercups and grasses, as well as some cereals. Continued debate over the commitment of Neolithic communities in Britain and Ireland to cereal cultivation (e.g. Stevens and Fuller 2012; Whitehouse *et al.* 2014; Bishop 2015) highlights the importance of reconstructing land-use at sites such as this.

A hypothesis-testing approach was used to explore two questions. First, the organisation of the land-cover elements around the hall and the size of the human-activity-modified area of landscape

were explored using a set of highly simplified landscape scenarios (Figure 6a). Once the probable size and composition of the modified area was known, this was inserted into a larger-scale map and pollen assemblages at the two existing large sites simulated (Figure 6b), to determine whether their pollen records could theoretically have recorded the presence of the clearing. The simplified models suggested that the modified area extended about 2.5 km from the 'hall'. Cereal cultivation seems to have been the most important land-use type close to the 'hall', and the wider landscape was a mixture of stands of hazel scrub woodland and open grassland rather than showing clear zonation with distance (Tipping *et al.* 2009). In simulation, pollen from types found only in the modified area was only recorded in the large sites at levels below 5%, which are comparable with those expected from natural forest (where small patches of non-tree-dominated habitat like glades or river banks will naturally occur and support populations of open-ground taxa).

These results emphasise the importance of site selection in research design – the large wetlands at Loch of Park and the Red Moss of Candyglirach have a correspondingly large pollen source area, and hence reflect regional vegetation composition. Small-scale woodland disturbance and cultivation of the type that took place at Warren Field is simply not detectable in the pollen records from large sites such as these. Detection of this type of activity requires analysis of deposits that reflect its small-scale nature, including those that are generally considered a low priority for palynological investigation due to perceived taphonomic issues (Tipping *et al.* 2009).

5. Case study 3: woodland management

A major form of human modification of woodlands takes the form of periodic cutting of limbs from broad-leaved trees and shrubs to generate regrowths, used for a variety of purposes, including fuel and animal fodder. Cutting occurs at ground level (coppicing), above the height of grazing animals (pollarding) or of the side branches only leaving the main trunk intact (shredding). An entire stand of woodland may be cut, cut trees may be intermingled with uncut trees, known as 'standards' or 'maidens', preserved for other uses (e.g. large construction timbers), or woodlands may be divided into sections for cutting in different years (Rackham 1990). Researchers have speculated about the effect of such practices on the pollen signal, acknowledging the complicated interacting effects of pollen site and woodland size and type, the tree species involved, and the frequency and method of cutting adopted.

A recent study of the impacts of coppicing on the pollen productivity and pollen signal of three commonly managed tree species (*Alnus glutinosa*, *Corylus avellana* and *Tilia cordata*) in several

managed woodlands in eastern England confirms the complexity of the problem. By combining studies of the flowering and pollen production of individual regrowths of different ages, Tauber trap records of pollen signals within compartments cut at different dates and short-core studies from small ponds within woodland settings with known coppicing histories, Waller *et al.* (2012) showed that species responded differently to management. For *Tilia cordata* and *Alnus glutinosa*, the amount of pollen produced was substantially reduced even under long (20 year plus) cutting intervals, and indeed *Tilia cordata* was likely to be ‘palynologically silent’ under most coppicing regimes described in historical documents. *Corylus avellana* on the other hand remained palynologically visible under even the shortest likely cutting regime, and seems to show enhanced pollen production in the early phase of regrowth, although this effect is moderated by different light competition regimes from standards and density of understorey or other coppiced species. Evidence from pollen traps (see also Bunting *et al.* 2016a, 2016b) and short cores taken from small ponds confirmed that no clear pollen signature for the identification of coppice rotations could be identified, probably because the effective pollen source area of even the smallest of sites includes compartments cut at different times as well as unmanaged areas, although cutting of the compartment containing a sampled pond was often accompanied by a clear signal of erosional input. The shifts in pollen production created by coppicing were incorporated into simulations, and produced changes in the pollen signal consistent with changes recorded in pollen diagrams from times and places in temperate Europe where woodland management is likely to have been adopted. Figure 7 shows a simple pollen diagram simulated for a pond in mixed woodland where coppicing of *Tilia* and *Corylus* is introduced, first on a long cutting cycle (any one patch of woodland is allowed to regrow for 30 years after cutting) and then on a shorter cycle (ten year gaps between cutting). It is assumed that management has no effect on the actual abundance of individual plants of each type, just on their pollen production per unit area. The effects on the pollen signal are clear, with an increase in the proportion of *Corylus* and *Quercus* (which is not actually being managed in this scenario) and marked decrease in *Tilia* proportions, especially under the shorter coppicing cycle regime. Woodland management therefore seems a plausible explanation for the decline in *Tilia* pollen seen widely across lowland England in the later prehistoric period (e.g. Grant *et al.* 2011).

This study shows the potential insights available from systematic study of the effects of management on pollen signals, and needs to be extended to other species and to other forms of woodland management.

6. Summary

Despite the abundance of arboreal pollen in sedimentary archives, reconstructing past woodland from pollen records is not straightforward. Modern pollen assemblages, which can be directly related to vegetation, and simulation tools can help researchers understand the limitations of their methods, test hypotheses derived from other lines of evidence against pollen data, and make informed choices about site selection for further pollen analysis. Simulation models are not perfect – for example, pollen productivity is assumed to be constant in most cases, yet research clearly shows that it varies in response to management and other environmental factors – but they do offer a valuable tool in helping palaeoecologists understand the range of possible past land-cover arrangements represented by pollen records and in developing more robust reconstructions which can more easily be communicated to collaborators from other disciplines.

In this paper, we have shown how surface sample data, simulation of pollen deposition in highly simplified and idealised landscapes, and use of environmental constraints and the Multiple Scenario Approach to land-cover reconstruction can develop and enrich the interpretation of pollen data through exploring three situations commonly encountered by environmental archaeologists. Ongoing international research collaborations are working on calibration and validation of the models for global use (for example through the PAGES Landcover6k working group: <http://www.pages-igbp.org/ini/wg/landcover6k/intro>). Increased understanding of the system that creates the pollen signal is improving our ability to both more accurately reconstruct the environmental context of past societies, and to appreciate and quantify the limits of our reconstructions.

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Figures

Figure 1: Comparison of the Multiple Scenario Approach and Landscape Reconstruction Algorithm methods for using the Prentice-Sugita model of pollen dispersal and deposition to reconstruct past land-cover from pollen samples from sedimentary records. The central grey box shows the importance of estimates of Relative Pollen Productivity, a key model input parameter, using studies of paired modern pollen samples and vegetation survey to both reconstruction methods.

Figure 2: Pollen representation of 10% tree cover in different landscape scenarios (see text and Supplementary Information for details of this simulation).

Figure 3: Results of MSA analysis for the Coigach Peninsula, constrained by the pollen record from Badentarbet (see text for details). a) possible mapped reconstruction of land-cover around 5200 BP (pale grey = birch-hazel woodland, other greys = other woodland types, dark grey = open communities) b) possible mapped reconstruction of land-cover around 300 BP c) summary of proportions of landcover types reconstructed via the MSA for five points in the later Holocene.

Figure 4: Location of case studies: 1. Assynt-Coigach (case study 1, Figures 3 and 5); 2. Hobbister (case study 1, figure 5); 3. Temple Wood (case study 2); 4. Warren Field (case study 2, figure 6); eastern England (case study 3).

Figure 5: Pollen signals around woodland fragments in a largely treeless landscape. A) field data from birch-dominated woodland in Assynt, north-west Scotland (Bunting 2002; see Figure 4 for location) plotted with simulation data from a simplified upland landscape (see Appendix for model parameters). B) Palaeoecological data from Hobbister, Orkney (Farrell 2015; see Figure 4 for location). Two peat cores were taken in close proximity; the two curves show the total proportion of tree pollen types plotted against age, showing how the woodland signal declines over the onset of peat accumulation at different times despite the spatial proximity of the two cores.

Figure 6: Using simulations to explore the land-cover structure around the early Neolithic Hall at Warren Fields. a) the three elements of the land-cover which were varied to create a set of hypothetical landscapes. b) assessing the visibility of a human-modified area in a largely undisturbed landscape (pie charts show the simulated pollen assemblages from the two mires shown and from a small hollow in the centre of the clearing (shown in black for clarity). See case study 2 in the text for details.

Figure 7: Simulated pollen diagram showing changes resulting from coppicing of woodland elements (woodland composition remains the same). For details of simulation see Waller et al. (2012). Zonation labels indicate coppice regime: long = compartments cut on a 30-year cycle, short = compartments cut on a 10-year cycle.

Supplementary Information: Details of simulations used for parts of figures 2 and 5.

Figure 2: Pollen representation of 10% tree cover in different landscape scenarios (see text and Supplementary Information for details of this simulation).

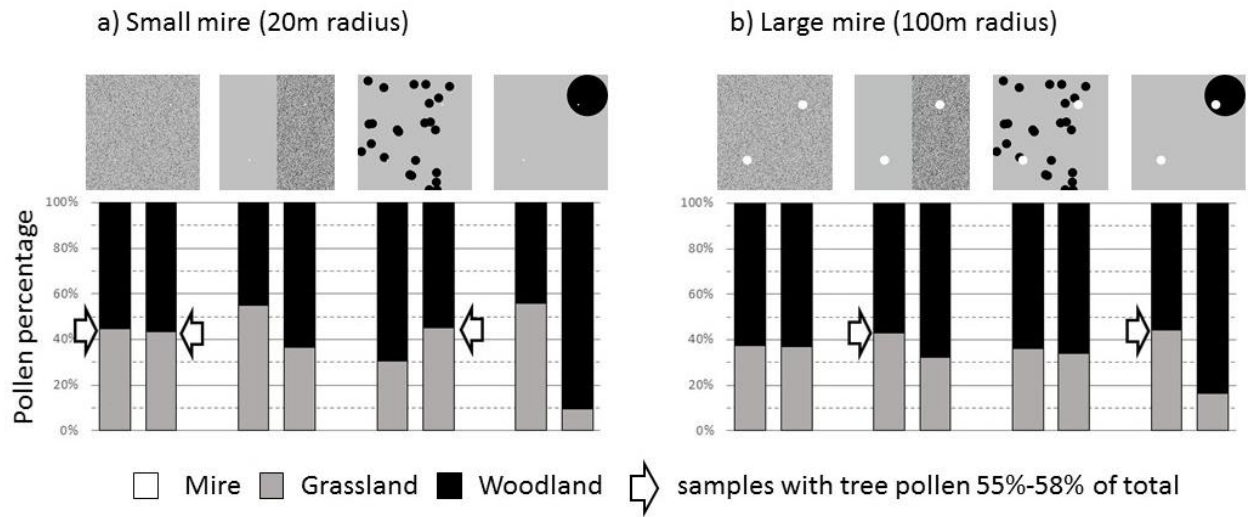


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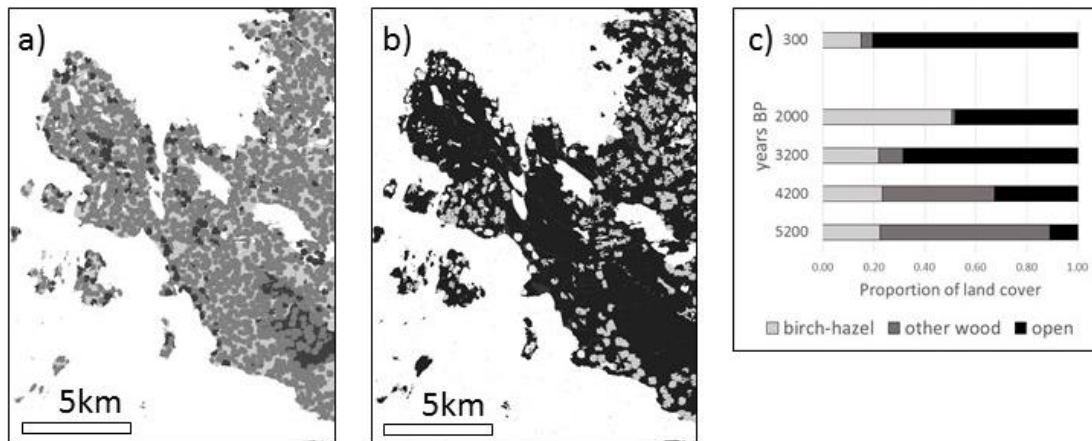


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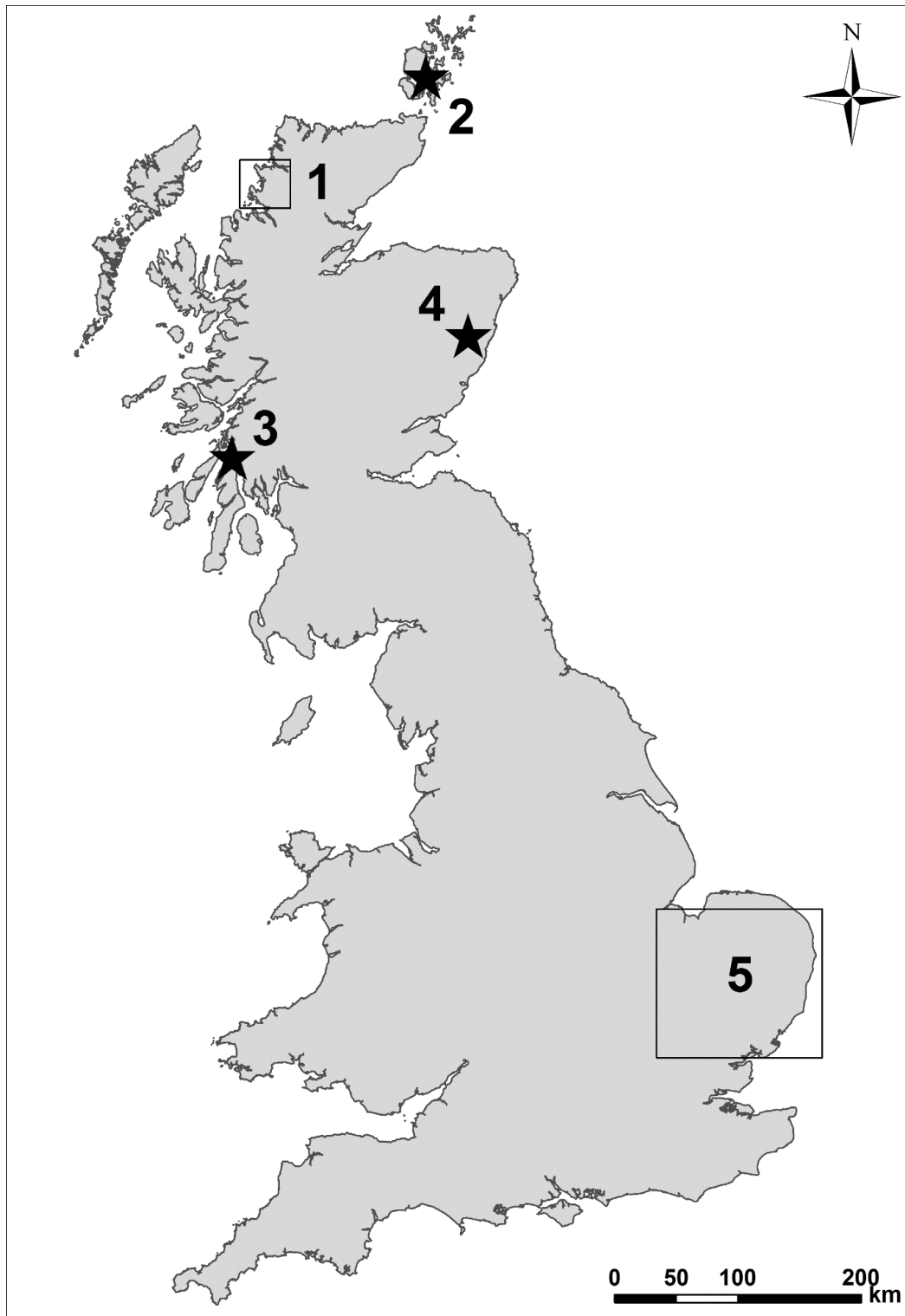


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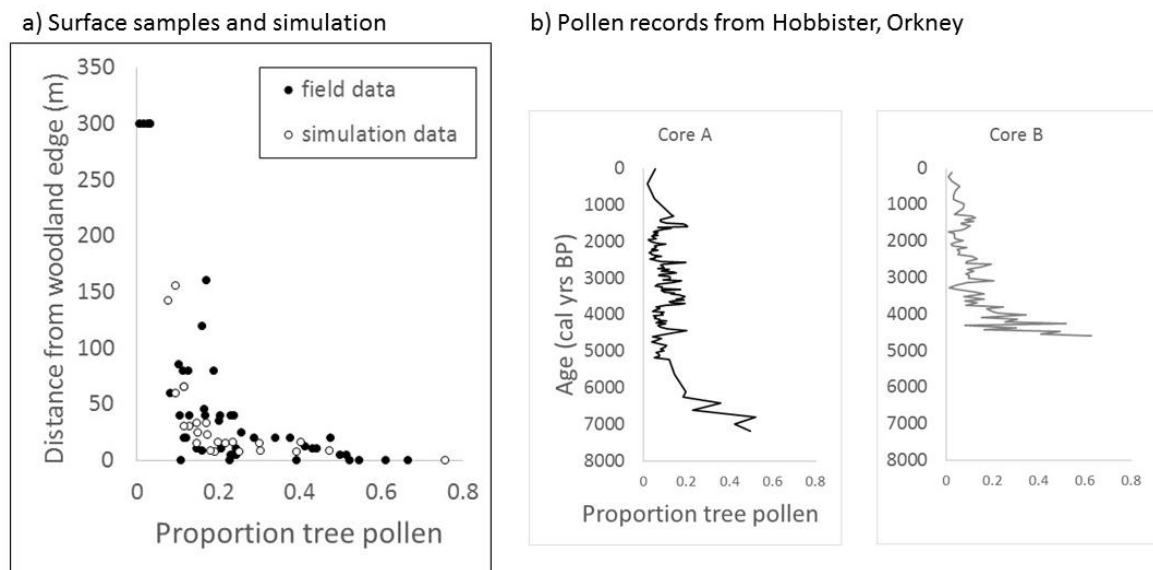


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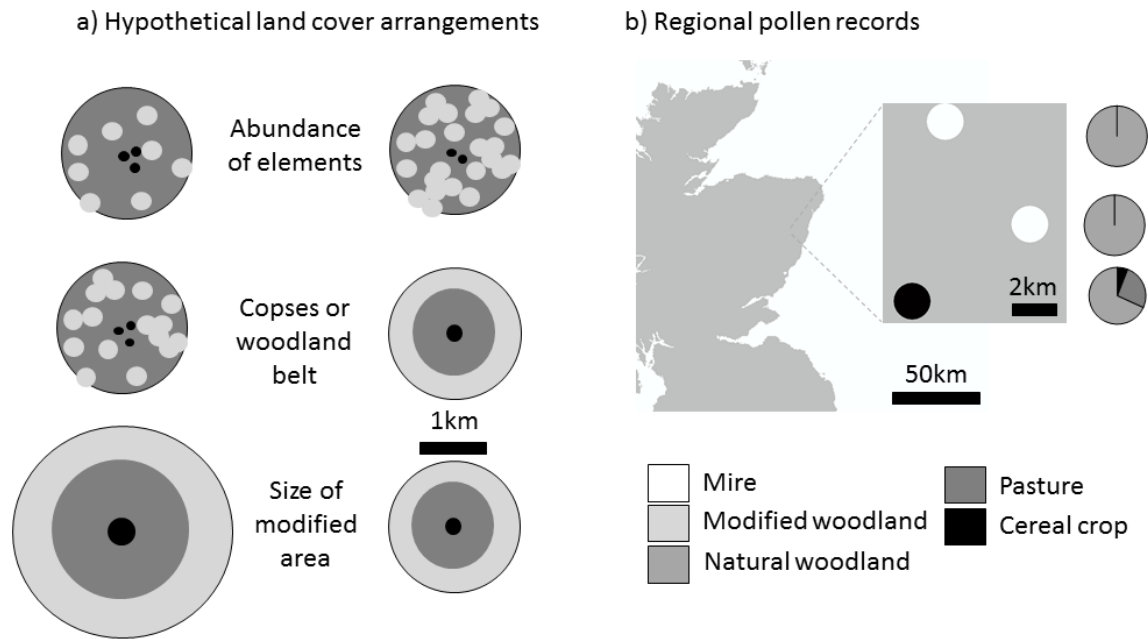
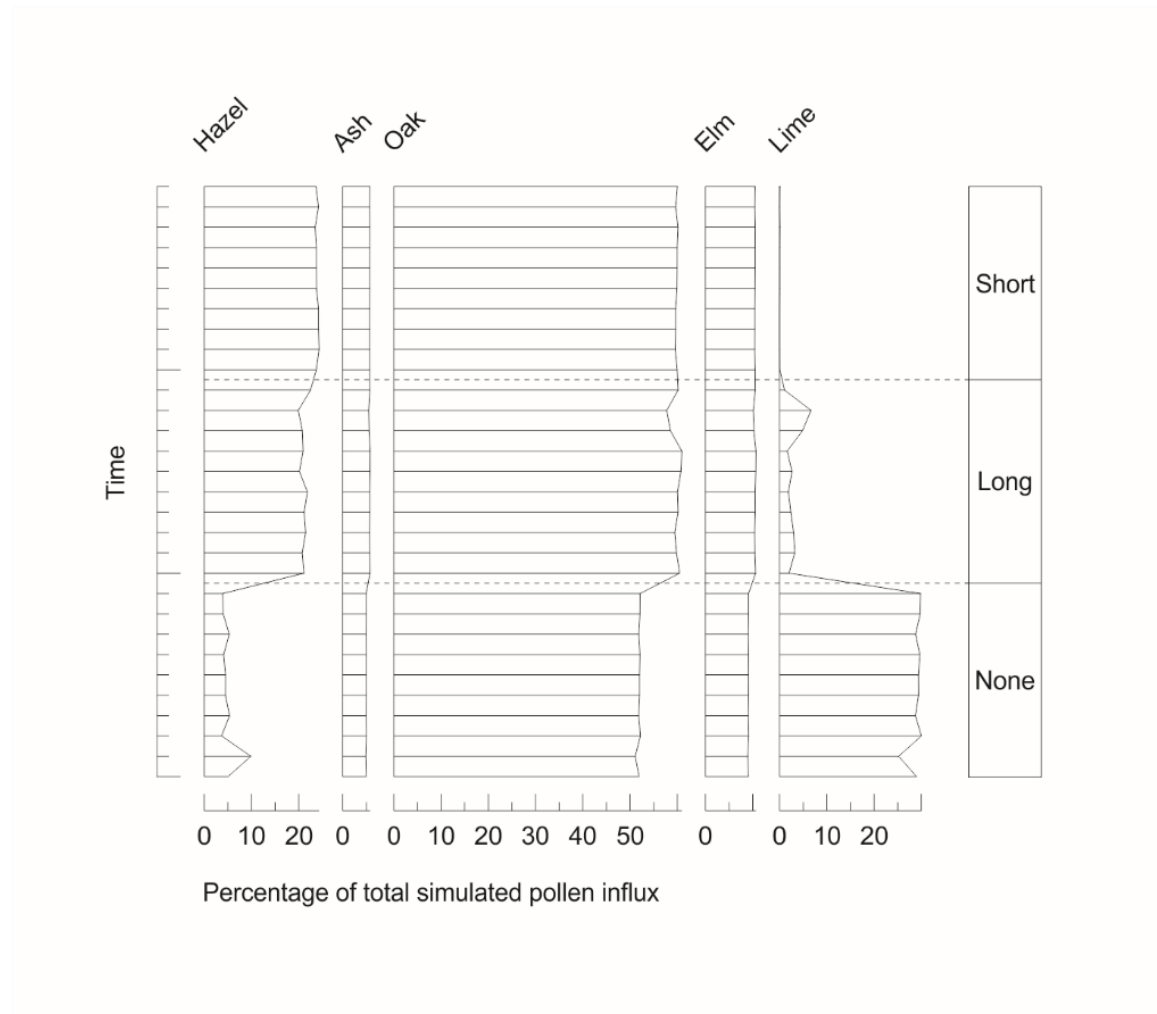


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Supplementary Information: model parameters for Figure 2 and Figure 5 simulations

Figure 2

Two grids were used, one nested inside the other

	Outer Grid	Inner Grid
Extent	20km x 20km	2500m x 2500m
Pixel size	50m	5m
Composition	50% wood 50% grass	10% wood 90% grass

Community properties:

Pollen producer	Fall-speed (cm s ⁻¹)	Relative Pollen Productivity	coverage	
			wood	grass
'grasses'	0.035	1	0	100
'tree'	0.030	4	100	0

The Prentice-Sutton model of pollen dispersal was applied within HUMPOLO with standard atmospheric parameters and a wind speed of 3 m s⁻¹.

Figure 5a

One grid was used

	Grid
Extent	2km x 2km
Pixel size	2m
Landscape composition	0.3% mire 46% open 1 23.1% open 2 23.1% open 3 7.5% wood

Community properties:

Pollen producer	Fall-speed (cm s ⁻¹)	Relative Pollen Productivity	Community composition				
			Mire	Open1 50% of matrix	Open2 25% of matrix	Open3 25% of matrix	Wood (40m radius circles)
Calluna	0.038	4	0	80	40	10	0
Grasses	0.030	1	0	10	60	10	0
Sedges	0.035	0.8	0	10	0	50	0
Birch	0.024	6	0	0	0	0	90

The Prentice-Sutton model of pollen dispersal was applied within HUMPOLO with standard atmospheric parameters and a wind speed of 3 m s⁻¹.

Pollen was simulated at points along two transects, one running 140m NW from the edge of a woodland patch across a mire and the other running 155m SW from the edge of the same patch through open vegetation communities, to mimic the range of the field dataset also shown on figure 5a, as shown in figure A1 below.

Figure A1: simulated surface sample pollen representation around a woodland fragment (see Figure 5 and main text). The white area is a mire community, the dark grey shades are the three open vegetation communities, and the pale grey circles are the woodland fragments. The black dash-dot line shows the simulated surface sample transect across the mire, and the white dash-dot line the transect through the open communities.

